

SENSITIVE DENDROMETERS FOR CONTEMPORARY RESEARCH. A CRITICAL EVALUATION OF STRAIN GAUGE DENDROMETERS

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ABSTRACT

The design and construction of very sensitive dendrometers using electrical resistance strain gauges is described. A number of circuits that can be used are discussed. The manner in which the sensors have to be attached to the plants is explicitly described, with information about necessary precautions being added.

Examples of the use of the instrument are given, showing their versatility, sensitivity and speed of response.

UITTREKSEL

SENSITIEWE DENDROMETERS VIR EIETDSE NAVORSING. 'N KRITIESE EVALUASIE VAN SPANNINGSMETERS VIR BOOM-METING

Die ontwerp en konstruksie van uiters sensitiewe dendrometers gebaseer op elektriese spanningsmeters word beskryf. Verskeie moontlike stroombane word bespreek. Die koppeling van die sensors ten opsigte van die plant is duidelik uiteengesit asook inligting rakende die nodige voorsorgmaatreëls wat geneem moet word.

Voorbeelde wat die gebruik van die instrumente, aanpasbaarheid, sensitiwiteit en reaksie tempo illustreer word ingesluit.

INTRODUCTION

There has been a long-standing need for a simple, continuous, non-destructive method for measuring the responses of plants to environmental variables. The daily stem contractions of woody plants, resulting from transpiration losses through the leaves, are well known. Attempts have been made to evaluate the relationship between these contractions and variations in temperature, light, relative humidity, and other environmental parameters (Holmes & Shim, 1968; Jordan & Ritchie, 1971; Klepper *et al.*, 1971; Namken *et al.*, 1969; Splinter, 1967, 1969; Stansell *et al.*, 1973; Turner & Waggoner, 1968; Zaerr, 1971). To satisfactorily evaluate these relationships, accurate and quick measurements of stem size must be made. To do so requires reliable and sensitive dendrometers and dendrographs. This paper describes the design and use of an electrical resistance strain-gauge technique for making such dendrographic measurements.

Accepted for publication 12th August, 1980.

Several investigators (Holmes & Shim, 1968; Jordan & Ritchie, 1971; Phipps & Gilbert, 1960) have reported diurnal fluctuations in stem diameter of up to 0.25 mm under high transpiration conditions. Smaller contractions of one-tenth this value are common. It is possible to measure these differences with calipers (Holmes & Shim, 1968), but this is discontinuous and insensitive. Phipps and Gilbert (1960) and Impens and Schalck (1965) used instruments that were far more sensitive but had to be bolted into the heartwood of the tree. Holmes and Shim (1968) drew attention to the large discrepancies in measurements taken with different dendrometers. In particular, the dendrometers that were bolted into the heartwood over-read, apparently because the drilling of the holes over-stimulated cambial growth. Splinter (1967) introduced linear variable displacement transducers (LVDT) to monitor changes in stem diameter. This resulted in a sensitive quick-responding dendrograph, with a resolution of 0.0025 mm in stem diameter.

A number of workers (Namken *et al.*, 1969; Stansell *et al.*, 1973; Klepper *et al.*, 1971; Jordan & Ritchie, 1971) have used this approach with considerable success. Unfortunately, an LVDT has to be mounted on a relatively large frame for attachment to a plant. It also has to be remounted every 20–30 days. Although the resolution is good for large diameter, it represents a larger part of the measured length as that length decreases. It is therefore, less accurate on smaller plants. Diametral measurements are also made with less accuracy than larger circumferential measurements.

Unfortunately, Splinter (1967) in his original paper discussing LVDTs, states that reliable strain gauge measurements, out-of-doors, are difficult to obtain, due to a number of reasons, including callousing of the stem, bonding creep over long periods of time, and thermal gradients across the measuring bridge. His opinion has apparently been widely accepted as fact, and authors such as Kinerson (1971) repeat these views about the unreliability of strain gauges without presenting any factual data to support the statements. In this paper it will be demonstrated that strain gauges are reliable, even for field studies. When correctly applied and incorporated into suitable circuits, they can be used to give highly accurate and versatile dendrographic data.

Whipple (1977) made a thorough survey of dendrographic methods and tabulated them to compare their performance features. It is clear from his ratings that the electrical resistance strain gauge dendrograph described here is generally superior to older methods in performance as well as convenience. When skillfully applied, this method is nondestructive: i.e., it does not harm the tree or affect its physiological behaviour. It measures "strain" (ϵ), which is the dimensionless ratio of change in length (Δl) to original length (l) ($\epsilon = \Delta l/l$) expressed in "parts per million" (ppm) or "microstrains" ($\mu\epsilon$). A resolution of $10 \mu\epsilon$ is readily achieved in long-term readings and, with care, a resolution of $5 \mu\epsilon$ (or under exceptional circumstances, $1 \mu\epsilon$) can be obtained. Since this is a dimen-

sionless number the resolution is the same for large or small plants whether taken on diameter or on circumference. On the same scale an LVDT would, on a 25 mm tree, resolve only 0.0025/25 or 100 $\mu\epsilon$, which is from 20 to 100 times less than can be achieved with strain gauges.

During nine years of development and testing at the University of Cape Town, Iowa State University, and Michigan Technological University (Schütte, 1970; Schütte & Burger, 1973; Whipple *et al.*, 1976), the strain gauge technique has proved to be highly reliable and easy to use under a wide variety of configurations and in many applications. Only a few elementary precautions are needed to obtain automatic, reliable, and continuous recordings of dendrographic data with a hitherto unattainable sensitivity and rate of response.

INSTRUMENTATION

Strain measurements with electrical resistance gauges is a highly sophisticated and widely used technique in the fields of measurement technology and experimental stress analysis. Strain gauges are today used extensively and imaginatively by engineers to solve many diverse measurement problems. They are, in fact, the active sensing elements in many high quality transducers for measuring pressures, flow rates, displacements, forces, etc. Through correct circuit design and intelligent application of the principles of solid mechanics, a researcher can compensate automatically for most of the effects which he considers to be extraneous to his system. Once the correct configurations and circuits have been established, the resulting measurement system is generally very accurate, rugged, and easy to use. In the light of contemporary technology, it is indeed surprising that they have not found use in the plant sciences as well.

Electrical resistance strain gauges operate on the principle that metal alloys experience a change in resistance when stretched. The alloys used for commercial strain gauges increase their resistance when stretched and decrease it when compressed. Thus, if a thin piece of foil is cemented to a surface and the surface is subsequently strained, the glue will transmit the strain to the foil, and the resultant resistance change will be directly related to the strain on the surface. This change in resistance (ΔR) is measured with a Wheatstone bridge and is related to strain through the relationship:

$$\text{Strain } (\epsilon) = \frac{\text{change in length}}{\text{original length}}$$

$$= \left(\frac{\Delta l}{l} \right) = \left(\frac{\Delta R}{R} \right) / S$$

$$\therefore \frac{\Delta R}{R} = S\epsilon$$

where S = the "gauge factor" or sensitivity to strain of the gauge

R = the unstrained resistance of the gauge.

For most commercial gauges, R is either 120 or 350 Ω and S is approximately 2.

Contemporary Wheatstone bridges and associated high quality amplifiers can measure the small changes of resistance which occur when a gauge is stretched and display the results directly as "strain" on any one of the large range of readout instruments. Digital voltmeters, galvanometers, and continuous strip chart recorders are widely used to display the results. The stability of these instruments over long periods of time and a wide range of environmental conditions is excellent so that long-term strains of 5 ppm ($5 \mu\epsilon$) can be read reliably and reproduced accurately. Over short periods, resolutions of $1 \mu\epsilon$ can be achieved. When applied to a circular object such as a tree trunk, the "circumferential" strain would, of course, be the same as the diametral strain. Thus, if a gauge is cemented tangentially to the trunk of a tree, it will read both diametral and circumferential changes to unprecedented accuracies. This data can readily be recorded automatically and continuously without the need for surveillance.

Figure 1 (a) shows an enlarged reproduction of a typical strain gauge. Most of the gauges used in the research described here had a gauge length (A) of 6,35 mm, overall length (C) of 9,53 mm, and overall width (B) of 3,16 mm. Smaller gauges were used on small trees. When both vertical and tangential strains were measured, a combined gauge incorporating two grids normal to each other on the same backing strip was used [Fig. 1 (b)]. The gauges are very thin and flexible and handle much like postage stamps. They cost from R1,50 each and come in many shapes and sizes, as a cursory glance at any catalogue will reveal. The selection of the correct gauge is important for the success of a project.

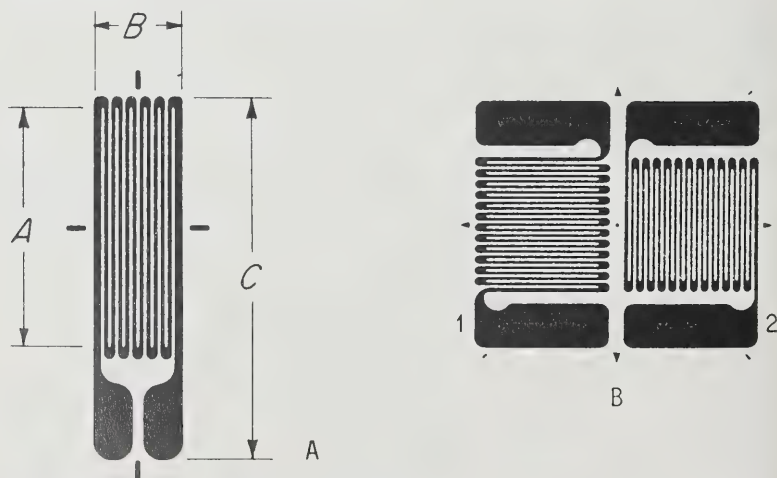


FIG. 1.

Enlarged view of two typical strain-gauge patterns used on trees. A = gauge length; B = gauge width; C = overall grid length.

The ones used by the authors of this work were constantan foil gauges on polyimide backing material. The preferred option was with an encapsulated grid and leads attached. Both 120 Ω and 350 Ω gauges were used, but the former was preferred because of availability and lower cost. The 350 Ω gauges are better, however, because they give larger readout voltages on a Wheatstone bridge and, therefore, require less "sensitivity" from the associated equipment.

POTENTIAL SOURCES OF ERROR

Since strain gauges are so sensitive, it is desirable to use them as accurately as possible. In applying them to trees certain difficulties are encountered which have not been resolved.

The first difficulty is due to changes in environmental temperature: the effect of such changes on the thermal expansion and contraction of the wood and the bark of a tree is very complex. It is not only different in the vertical (axial) and tangential or diametral directions but also varies with the state of hydration of the tree. There is no "typical" coefficient of thermal expansion for the trunk of a living tree. When quasi-equilibrium temperature conditions are disturbed, stable conditions may not be re-established for several hours. In one test the authors imposed a 20 °C cycle for 20 min on the stem of a small (40 mm diameter) tree. The thermal expansion effects caused by this cycle could still be observed 6 hr after normal temperatures had been re-established on the bark.

Despite these anomalous changes, however, the maximum changes can be estimated through carefully set-up measurements (Whipple *et al.*, 1976). They are small compared to the real strain changes that occur over the same time intervals. By careful design of the whole measurement system these errors can be kept to less than 5 % of the strain readings.

It should be pointed out that this error is, and has been, present, to the same or to a larger extent, in all other dendrographic measurements, and it is much harder to do even partial compensation in alternative systems. A good quality strain-gauge system will have smaller errors due to uncompensated thermal expansions than any other dendrograph currently in use.

The second potential source of error derives from the possibility of long-term "creep" in the adhesive layer between the gauge and the tree. The adhesives in general use do not display this tendency when used in regular industrial applications, but their long-term stability when used on live trees has not been fully established. When dealing with living material which shows growth responses to pressures and gravity, it is not easy to design long-term adhesive "creep" tests along traditional engineering lines.

In one investigation tests were run for 24-hr periods during which two opposing vertical gauges were mounted on a trunk of a tree which was bent to give readings of plus and minus 1 000 $\mu\epsilon$ on the tension and compression gauges, respectively. The load was maintained for 24 hr, and the creep was observed.

Long-term physiological adjustments to the bending stem, similar to those alluded to in the discussion on temperature effects, occurred but did not obscure the conclusion that creep, if any, was less than 2 % of the strain reading. Especially clear evidence was obtained from tests that lasted only 8 hr but were performed during the night-time non-transpiring period when the trees did not experience regular physiologically induced strains. *Creep will reduce the strain readings to below their real values.*

The third potential source of error on the use of strain-gauge dendrometers arises when they are being used to measure short-term growth. Since these instruments are very sensitive, they record changes in girth very readily and very rapidly. There is always the temptation to consider these changes in girth as signs of growth. For example, the daily increments observed at the night-time rest condition are not necessarily "growth". These changes may even show negative values for several days simply because the plant suffered a little water stress and was unable to recover fully. Daily increments are not a good measure of growth, unless they are made when the stem is under no water stress. For best results the pattern should be observed over a period of several days.

The fourth source of error results from the possibility that the strain-gauge "backing" material and glue reinforce the bark at the point of application. The bark is then "stiffer" in this region, and the observed strain is less than would have occurred in an unreinforced area. This is especially likely on soft green bark and on very young plants. The authors minimized this error by selecting polyimide backed gauges which are soft, very pliable, and have a modulus lower than most biological materials. The cement was Eastman 910 which, if carefully applied, gives a very thin, high elongation joint which is essentially creep free under most conditions. We do not consider this an important problem in the trees on which we took measurements, but it remains an error that should be guarded against since it is hard to evaluate its effect in any other than an analytical way.

A fifth source of error is the apparent strain that arises when moisture "short circuits" the gauge between the foil grids of a gauge. This leads to small changes in the resistance of the grid which will, of course, appear to be compressive strains. Fully encapsulated polyimide gauges do not have this problem, and in many checks during the night-time "rest period" of our experimental trees we never had any indications that moisture affected the gauges.

The linear strain range for constantan foil gauges is $\pm 5\%$ (50 000 $\mu\epsilon$). If larger strains are expected, annealed constantan (P-alloy) gauges can be used for ranges up to 20 % (200 000 $\mu\epsilon$). For special purposes and long-term growth studies, liquid metal gauges with capabilities of up to 200 % strain are available. Nonlinearity of the gauges is therefore not a problem. Good instruments should also have a linear range. One range should, however, be checked to insure that all voltage readings are linearly related to strain.

TECHNIQUES

The authors have used strain gauges in three basic ways. In the first, the gauges were mounted on a thin metal strap which was wrapped around the tree like a belt. Here, the measurement was the strain on the belt rather than on the tree, and since the belt was much stiffer than the trunk, the output was more precisely a measure of the internal pressure which the expanding and contracting tree applied to the belt than the actual strain in the tree. Signatures of changes were, however, accurate, compensation for temperature was complete, and long-term stability of the adhesive layer was of the highest order. These belts can be moved from tree to tree and are of particular value in field studies on mature trees with rough bark.

The second method is the one described here and is the only real "strain" measurement. The gauges are cemented directly onto the tree as described in a previous paper (Whipple *et al.*, 1976). They read, directly, the tangential strain on the tree. This reference reports on the initial responses observed on a red maple tree (*Acer rubrum*). It also discusses the errors involved and the means by which they may be eliminated. The effects of temperature variations are also considered.

In the third technique, strain gauges are used as active sensing agents on transducers which are clamped to the trees: they measure diametral changes of the stems. The concept is the same as with LVDTs except that temperature compensation can be better, and the device much lighter, more rugged, and has a better resolution.

CIRCUITS

For static or quasi-static strains, such as appear in dendrography, the Wheatstone bridge is the preferred way to measure the small resistance changes that occur in strain gauges. It is generally drawn as shown in Figure 2 with equal resistances in each of the four arms. One, two, or all four of the resistances may be replaced by strain gauges to form a bridge with one, two or four "active" arms. These are known as "quarter", "half" and "full" bridge hookups, respectively. It is customary for the "fixed" resistors to have the same value as the gauges which are being used. Most "bridge networks" provide a stable excitation voltage which should be as low as possible when gauges are used on live tissue. The gauge current will then be low, and the gauge will be able to dissipate the heat without affecting the tissues to which it is glued. One and one-half volts (1.5 V) applied to a 120 Ω bridge will yield a gauge current of only 6.3 milliamps. The heat generated by such a system will be readily dissipated.

If a tree is reasonably axisymmetric, bending and torsional effects can be compensated for by mounting two gauges diametrically opposite to each other on the trunk and hooking them into opposite arms of the bridge. Further details

are given in Holister (1967). It is important to keep all leads between the bridges and gauges of equal length, and to expose them to the same temperature. Failure to do so will cause unbalance of the bridge because of resistance changes in the leads (Holister, 1967).

Single-arm bridges do not compensate for bending nor for errors caused by differential thermal expansion between gauges and the material on which they are mounted. In many investigations these errors are small enough to be neglected when compared to the much larger physiologically induced strains which are being measured. In those cases single-gauge installations are economical and effective. The "three-wire" hookup to the gauge [Fig. 2 (c)] should always be used to equalize the lead resistance included in two adjacent bridge arms.

A four-arm bridge [Fig. 2 (a)] is usually the best arrangement. It is also the most expensive. The preferred configuration is to glue two double gauges [Fig. 1 (b)] diametrically opposite each other onto the trunk of a tree that is straight, round, and axisymmetric in structure. (Trees meeting this requirement may be difficult to find, but reasonably close approximations are adequate for most studies). In each pair one gauge will be horizontal and the other vertical. Bending stresses will then be compressive on one pair and tensile on the other. There will be no normal (extension or compressive) strains in the gauge directions caused by torsion, and each pair will sense identical physiological strains. When wired into the bridge so that the two tangential gauges are in opposite arms and the two vertical gauges in the remaining arms, bending stresses will cause no unbalance while physiological strains will be additive. If the thermal expansions are the same in the vertical and horizontal directions, all four gauges will experience equal strains caused by differential expansion between the tree and gauge, and

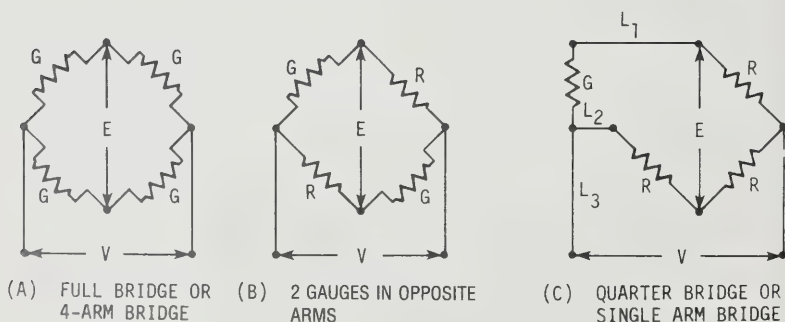


FIG. 2.

Three bridge arrangements used on trees to measure changes in girth. G = active gauge; V = excitation voltage; R = internal balance resistor; E = output as signal voltage; L_1 , L_2 , L_3 = three leads of equal length to single active gauge at a remote position. See text for details of usage.

no unbalance will appear on the bridge. Temperature compensation will be complete. If the further assumption is made that there is no vertical response caused by diurnal cycles or by growth, the vertical gauges will have zero readings from physiological effects. The whole arrangement will be doubly sensitive to tangential changes and insensitive to all the usual errors. Such a system would be ideal.

Unfortunately, live trees sometimes behave in most unusual ways. The authors have observed significant vertical responses in a few isolated instances. In order to separate these responses from the tangential ones, the vertical gauges should be removed from the bridge, which will then have only two gauges in opposite arms. Bending and torsional strains will still cause no unbalance, but differential thermal expansions will introduce errors in the two active gauges. In this setup the strains measured by the two gauges as well as the thermal effects are additive.

This leads to consideration of the quarter bridge with a single active gauge mounted tangentially on the trunk and hooked into the bridge with three wires as shown in Figure 2 (c). This gauge will be fully sensitive to tangential strains and record them directly on the readout instrument with a factor of one because only a single gauge is functional. Strains caused by differential thermal expansion between the gauge alloy and the tree, will, likewise, be recorded with a factor of one and appear as an apparent strain which cannot be separated from the real strain unless the relative coefficients of expansion are known and the bark temperature is simultaneously recorded. In Whipple (1977) and Whipple *et al.*, (1976) these temperature effects have been shown to be much smaller than the physiologically induced strains so that the error is small. How small will depend on the tree species, the state of the tree, and the range of temperature variation. For the maple tree used in Whipple (1977) and Whipple *et al.*, (1976), the largest error was only 2 %

For a straight and axisymmetric trunk, no strains will be recorded due to twisting of the tree. Bending will have a small effect. The cross sensitivity of modern foil gauges (i.e., the sensitivity to strains normal to the gauge length) is usually about +1 %. Thus, a severe bending strain, 100 $\mu\epsilon$ tension, will cause an apparent tangential reading from the source of 1 $\mu\epsilon$. That same tensile strain will, however, cause a compressive strain in the gauge direction due to Poisson's effect of -20 to -30 $\mu\epsilon$. Poisson's ratio for a specific tree may be estimated by comparing the bending strains recorded by a vertical gauge to that of a horizontal gauge. For most trees tested in this programme, the ratio was between -0.2 and -0.3. Oscillations due to wind loads will, therefore, be between 20 % and 30 % of the resulting bending strains.

In a greenhouse such strains are small and may readily be ignored. In the field light breezes seldom introduce strain which is large by comparison with the response readings. If this is troublesome two gauges in opposite ends have to be used for compensation [Fig. 2 (b)]. The temperature error will not be affected

since it will be the same percentage of the reading on each of the gauges. Thus, for indoor studies, the quarter bridge arrangement is often an economical and accurate alternative to more involved systems. The authors have used it extensively in their investigations.

MOUNTING STRAIN GAUGES

Details of one method for mounting gauges are given in Whipple *et al.* (1976). Another method which gives good results for shorter term investigations employs Eastman 910 cement and catalyst (Micromeasurements Instruction Bulletin B127). The procedure is as follows: Lightly sandpaper a small area on a smooth, straight, and round portion of the stem where the gauge is to be mounted. Wipe the area with cotton dipped in acetone or trichlorethylene to temporarily remove grease and dampness. Warm and dry the area by gently blowing hot air onto it with a hairdryer. This provides a slightly warm base for the adhesive which will then cure more quickly. Place the gauge right side up on a clean piece of glass. Overlay it with a 100 mm strip of transparent adhesive tape. The gauge will then stick to the tape. Lift the tape from the glass and transfer the tape and gauge to the tree. Locate the gauge in the correct position and push the tape down to hold the gauge in place. Peel back one end of the tape until the gauge is just off the tree. Apply a very small amount of catalyst to the bark as well as to the back of the gauge and make sure it is dry. Apply a drop of adhesive in the corner between the gauge and the tree and roll the gauge down with the thumb. This spreads the cement evenly and prevents air bubbles from being trapped under the gauge.

The tape should be wide enough so that no cement is squeezed past its edge and comes in contact with the thumb. Apply pressure with the thumb for one minute. Keep applying gentle heat for another 5 min to accelerate the drying process. Solder lead wires to preattached leads and connect to the bridge and readout device. Keep excitation voltage on for 12 hr to maintain the temperature at the glue line. The gauge is now ready for use and will function well for periods of up to eight months. If the gauge is not encapsulated, waterproof the gauge with a thin coating of a suitably flexible agent. The final installation will then have only small reinforcing effects on the bark and will respond very rapidly to strains in the trunk.

Do not attempt to solder directly to the gauge tabs after the gauge has been mounted. The slightest heat from the soldering iron will burn the tree underneath the tab. Callous tissue then forms rapidly and lifts the gauge from the tree. If gauges without preattached leads are used, all lead connections must be made before mounting the gauge.

Eastman 910 cement is single component contact curing cement which is very suitable for polyimide backed gauges. It sets rapidly under thumb pressure but is only fully cured after 12 hr. The performance of the adhesive deteriorates with

time and moisture absorption. The performance of the installation must, therefore, be checked at regular intervals. Solar heating of the gauges must be precluded by covering with cotton or an alumina shield.

The technique for mounting gauges described in Whipple *et al.*, 1976, has better long-term stability but causes more reinforcement. It is best suited to older trees and stiffer bark.

THE INSTRUMENT IN USE

A number of examples of the type of investigation that can be conducted with this equipment are now discussed to show the sensitivity and versatility of this instrument. Details of the experimental investigations and their implications will be treated in other communications.

An individual strain gauge mounted directly onto a tree will read the average strain over the gauge length. It does not read the strains that occur elsewhere around the circumference. If these do not differ significantly from point to point, then a single gauge will do a good job of monitoring the strains in the trunk. If it is required to average over larger lengths, longer gauges are needed or multiple gauges should be mounted in series around the circumference. Foil gauges are generally available up to 50 mm long. Special purpose gauges up to 500 mm long can be obtained.

Example No. 1

A solution for averaging strains over the whole circumference of a tree is to use the thin metal belt discussed before. As an example of the use of belt mounted gauges for field duties, the case of a *Prunus domestica* tree, 107 mm diameter is cited. The *Prunus* tree grew in a sheltered situation in a well-watered and overcrowded garden in the University of Cape Town. The soil was heavy clay. Crowding, soil conditions and restricted light resulted in slow growth and dense wood, but the tree was not deformed in any way. The tree was studied by means of a portable strain bridge and a belt made from bronze shim material 25 mm wide and 0.25 mm thick. A lace-through buckle permitted continuous adjustment so that the belt could be made to fit snugly around the trunk of the tree.

Figure 3 presents the point by point data collected from this over a 28 hr period. The night-time strain is taken as "zero" so that all strains are compressive. The stem fluctuations were almost $80 \mu\epsilon$, which in this case is a diameter change of 0.00860 mm. The stem fluctuations follow the well-known pattern of diurnal stem contractions and are obviously related to environmental parameters such as temperature. Despite the fact that the readings are of an intermittent nature and the belt technique is not the most sensitive form of strain gauge dendrometer, the instrument records considerable detail concerning the short-term variation in the girth of the tree.

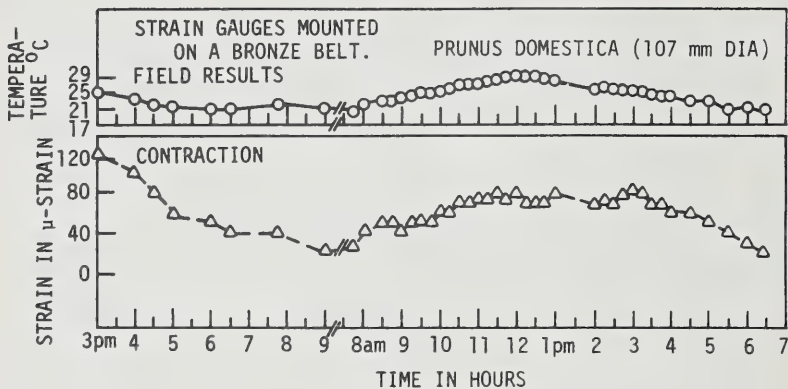


FIG. 3.

Diurnal cycle of ambient temperature and stem contraction data from strain gauges mounted upon a bronze belt around the trunk of a *Prunus domestica* tree, with a stem diameter of 107 mm at 1 m above ground.

Example No. 2

Under the more controlled conditions of a greenhouse, it is possible to utilize the sensitivity and rapid response of the strain-gauge dendrograph more fully. This is well demonstrated by the responses of a drought stricken 1.3 m tall *Acacia cyanophylla* tree grown in a 15-litre pot of clay soil (Fig. 4). Its stem diameter was 18 mm. To investigate the stem responses, a quarter bridge was used and the gauge mounted directly on the stem 126 mm above the soil line. *A. cyanophylla* is adapted to regular water stress, but this plant was subjected to very severe water stress by not watering for eight days. In spite of this it showed a rapid response to light and temperature. Minimum girth (maximum strain) was reached at 11h00 with a contraction of 740 $\mu\epsilon$. The rate of change of strain during the preceding hour was very high (230 $\mu\epsilon$ /hr, representing a diameter contraction of 0.0045 mm). After 11h00 the rate flattened out until the tree was watered at about 13h00.

The influence of light upon the stem contractions can be seen at 09h45. The tree was temporarily shaded from direct sunlight by placing a cloth screen between it and the incoming light. (Lateral light was not excluded.) The result was an immediate reduction in strain (expansion of the trunk) of 125 $\mu\epsilon$ in 15 min. This very rapid response was completely reversible. When the shade screen was removed, the strain returned to its original level. The magnitude of the *light response* depends upon the time of the day and the physiological state of the plant. It can be measured rapidly and accurately.

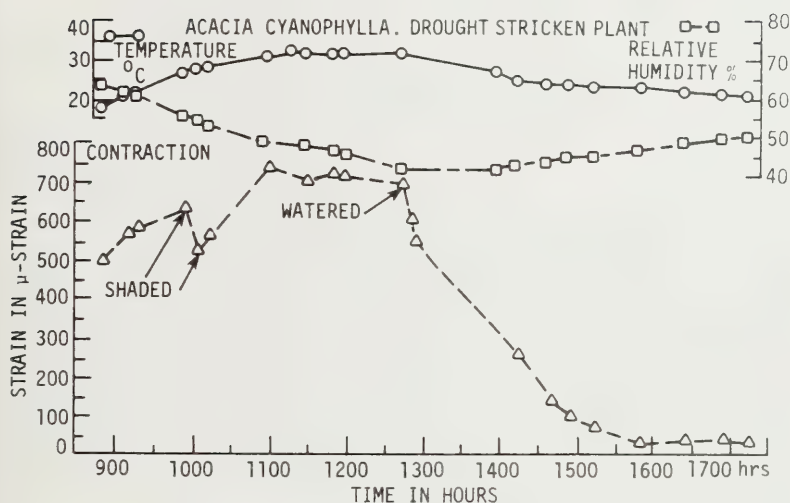


FIG. 4.

Glasshouse studies on pot grown *Acacia cyanophylla*. Strain gauges were mounted directly onto stem. The plant was very severely drought stricken, yet responded to light by contracting its stem. Shading resulted in an immediate response whereby the stem expanded. On re-exposure to light, contraction continued to a maximum at which level it stayed. Response to watering was immediate and very dramatic, concluding at just before 1600 hours.

The relationship between stem behaviour and the hot dry environment can be observed.

The *watering response* at 13h00 is dramatic. It appeared within 4 sec of the plant being watered. (See Fig. 5 for details of water response.) Expansion of the stem due to watering continued until almost 16h00. The overall recovery was a most impressive $660 \mu\epsilon$ in 3 hr. Although this response is dramatic on the graph, it represents a change of only 0.0117 mm in diameter. The dendrograph measured this effect readily and about instantaneously.

Example No. 3

Continuous recordings give much more versatility to the experimenter, by enabling him to measure lag and response times accurately. The degree of accuracy and sensitivity achievable is demonstrated in Figure 5, where the response to watering in *Populus alba* $\times$ *dentata* was investigated. This plant was grown in a horticultural potting mixture in the greenhouse, and its general strain response to watering was known to be rapid. Upon accurate investigation, it could be shown that the stem completely reversed its daytime pattern of contraction and started to expand within less than 3 sec of water being supplied to the

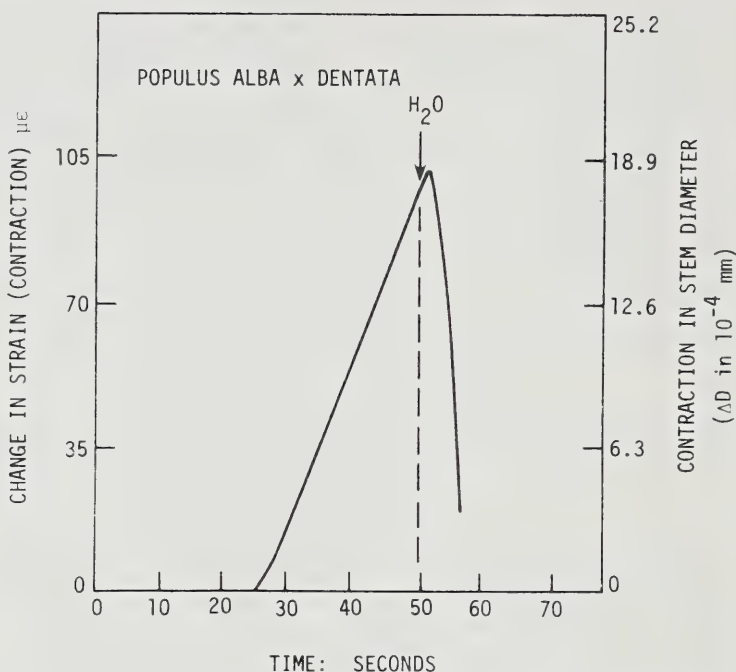


FIG. 5.

Rapidity of watering response: glasshouse grown *Populus alba* $\times$ *dentata* had strain gauges directly mounted on its stem. The stem was contracting steadily, as the recording shows. The plant was watered at the 50 second mark. Within less than 3 seconds of the water making contact with the soil, the entire trunk had ceased to contract and started to expand at a spectacularly rapid rate.

pot. Allowing for the time it took the water to reach the roots, this must be considered an almost instantaneous reversal of strain. In the subsequent 5 sec, the change in strain was $85 \mu\epsilon$. (This is a dimensional change of 15×10^{-4} mm in 5 sec in a stem 18 mm in diameter.) This type of result is reproducible. Its significance will be discussed in a subsequent publication.

Example No. 4

The light reaction is equally amenable to experimental investigation. A small *Populus alba* $\times$ *dentata* was kept in the dark for two days and then moved into deep shade. It was watered regularly to prevent any water deficits developing. It was placed under a bank of Photoflood lamps. The influence of various intensities of light upon the rate of contraction of the stem was studied for periods of

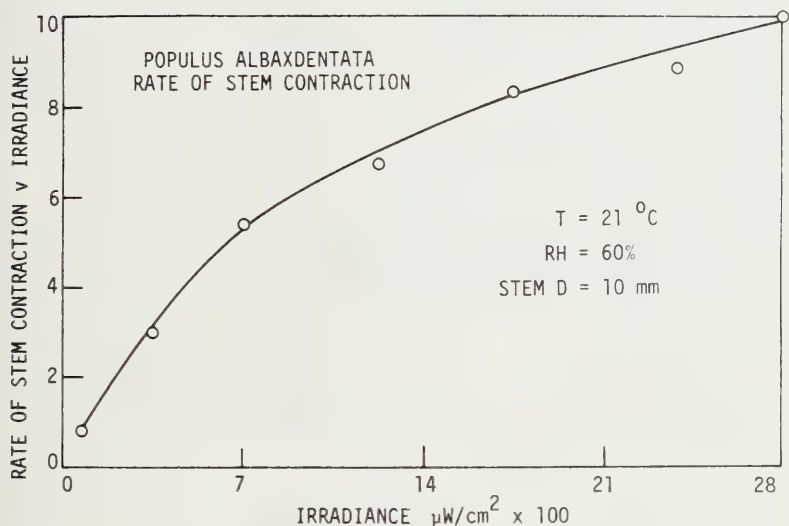


FIG. 6.

A study of the influence of light intensity upon the rate of stem contraction in *Populus alba* $\times$ *dentata* shows that at low light intensities the light is far more efficient per irradiance unit, in bringing about stem contractions, than it is at high intensities. The relationship is predictable.

10 min. During these times the response remained linear. There is a very clear relationship between the irradiance of the light and the stem contraction, as the results in Figure 6 show. The significant response to low light intensities which has been observed in the field and in other investigations, can be readily measured by these techniques, as they are associated with almost instant stem changes.

Example No. 5

Daytime oscillations characterise these dendograms (Fig. 7). The periodicity of the cycles appears to be characteristic of the species and ranges from 20 to 90 min in the plants investigated to date.

At higher sensitivities, other dynamic cycles with periods of less than a minute become evident (Fig. 8). They are particularly interesting because their amplitude and frequency are altered by watering. In Figure 8 the oscillations occur at periods of 30 sec to 90 sec and have an amplitude of about $1 \mu\epsilon$. Once again, these oscillations had no links with environmental or other external sources of "noise". They are quite persistent, and since their characteristics appear to alter with the state of stress of the trees, they may play an important part in studies of water relations.

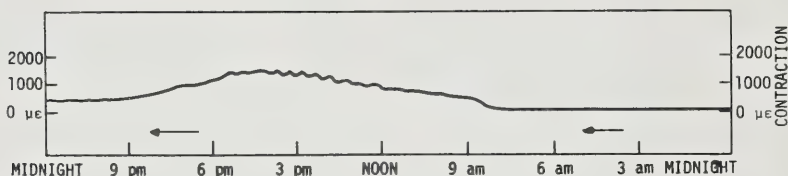


FIG. 7.

Continuous strip chart recording of stem girth for an entire day, showing the endogenous and characteristic oscillations during the daylight period, which are completely absent at night. The oscillations may have other effects superimposed upon them and are not always as clearly evident as in this recording.

Figure 8 is a gymnosperm *Podocarpus latifolius* and Table 1 shows the effect of watering on two species, *Populus* and *Alnus*. Changes in these oscillations are slower to occur than the first response of strain to watering. It may take up to 10 sec to be expressed clearly. While the exact nature of the phenomenon being recorded is unclear, it is compatible with the concept that hydration is altering the volume of the wave conducting tissues and so altering its frequency. There is reason to believe that this type of investigation may be of value in rehydration studies and in studying the path of water conduction in the stem.

There is uncertainty as to whether the small waves recorded in the latter study are similar to, or analogous with, slightly smaller waves of a much slower frequency observed previously in *Podocarpus* which is a gymnosperm and has a different type of anatomical structure.

DISCUSSION

Strain fluctuations vary greatly in magnitude from one species to another, even between trees of the same species but with different growth histories. Holmes and Shim (1968) reported average diurnal fluctuations in Canary Island Pines of 600 $\mu\epsilon$ in summer and 180 $\mu\epsilon$ in winter. The authors of this paper have observed daily fluctuations of around 1 000 $\mu\epsilon$ in a black poplar as well as in *Podocarpus latifolius*, 700 $\mu\epsilon$ in a red maple (Whipple *et al.*, 1976), and up to 6 000 $\mu\epsilon$ in a pot-grown *Populus* hybrid which was under water stress at the time. In cotton plants which are, of course, semi-herbaceous rather than woody, fluctuations of 26 000 $\mu\epsilon$ are not uncommon (Namken *et al.*, 1969). In this context, it is well to note that the light responses first observed by Namken *et al.* (1969) and Stansell *et al.* (1973) in cotton are considerably larger than those in the *Acacia* depicted in Figure 4. In cotton changes of up to 1 400 $\mu\epsilon$ in 5 min have been observed. But the stem girth fluctuations are also proportionately much greater in herbaceous plants than in woody plants. Woody plants with low

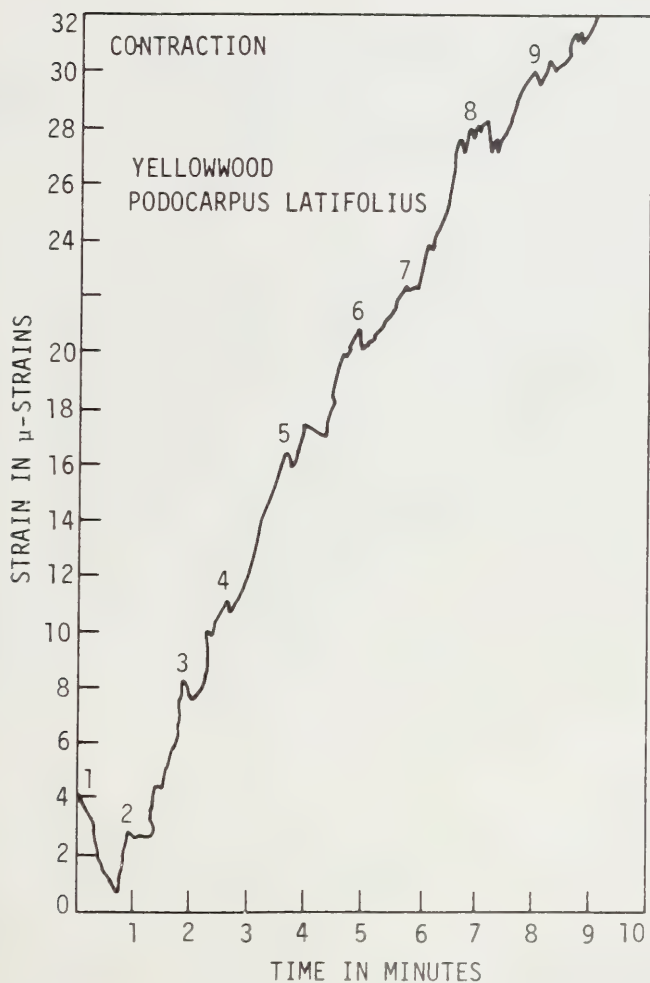


FIG. 8.

Short term, micro-oscillations are characteristic of all plants tested so far. The *Podocarpus latifolius* is a good example although in many plants the frequency will be greater.

TABLE 1.
Influence of Watering upon Micro-oscillations of Tree Stems

Plant	Treatment	Frequency, cycles/min	Amplitude, $\mu\epsilon$	Frequency $\times$ Amplitude
<i>Populus alba</i> $\times$ <i>dentata</i>	Before watering	100	1,75	175
	1 min after watering	256	0,70	179
	20 min after watering	112	1,75	196
<i>Alnus glutinosa</i> L.	Before watering	92	3,75	345
	10 min after watering	128	2,50	320

density woods and soft bark show greater fluctuations than ones with dense wood and compact bark. In all these plants, however, the pattern of the responses to environmental variables is very similar.

The fact that stem strain is such a sensitive index of the behaviour of a tree is of great importance. The strain patterns obtained with strain gauges reveal information about the entire plant, as a system, that is difficult to obtain by other means. Most of the detailed stem variations have not been observed previously. This data is hard to explain at this time because it takes us down to a tissue level that has not been accurately measured in dendrographic observations before. Future research will attempt to answer some of these questions.

CONCLUSIONS

Initial results from the use of strain gauges applied to the trunks of trees lead to the conclusions that:

1. Strain-gauge dendrography is a practical and adaptable technique for investigating water and environmentally related responses in trees.
2. The high degree of precision attainable allows detailed recording of water utilization and stress in trees.
3. The system measures light responses of intact trees.
4. The system is capable of yielding information about little known phenomena such as micropulses in tree stems.
5. Accurate growth measurements are possible and in need of detailed investigation.
6. This basic system is well suited to study water relations in trees. It will be particularly useful for studying water utilization.

ACKNOWLEDGEMENTS

This work was initially financed by a Staff Research Fund Grant from the University of Cape Town. It was further sponsored by the Departments of Forestry, of Engineering Science and Mechanics and the Graduate College of Iowa State University which bodies subsidized the sabbatical leave of one author (K.H.S.) and the costs of these studies. All assistance is gratefully acknowledged.

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